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Brushless DC Motor Drives

In conventional DC motors with brushes, the field winding is on the stator and armature winding is on the rotor. Because of the brushes, the motor is expensive and needs maintenance. In addition, accumulation of the brush debris, dust, and commutator surface wear as well as arcing cannot be permitted in certain hazardous locations, which limits the application of DC brushed motors. As solid-state switching devices have been developed, it became possible to replace the mechanical switching components (commutator and brushes) by electronic switches. In fact, a brushless DC (BLDC) motor has a permanent magnet rotor and a wound field stator, which is connected to a power electronic switching circuit. Rotor position information is required for the power electronic driver. [Figure 8.1](#) shows brushless DC motor drives and [Fig. 8.2](#) a typical BLDC motor.

According to the National Electrical Manufacturers Association (NEMA), “a brushless DC motor is a rotating self-synchronous



FIGURE 8.1 Brushless DC motor drives. (Courtesy MPC Products Corporation, Skokie, IL.)

machine with a permanent magnet rotor and with known rotor shaft positions for electronic commutation.” The advantage of brushless configuration in which the rotor (field) is inside the stator (armature) is simplicity of exiting the phase windings. Due to the absence of brushes, motor length is reduced as well. The disadvantages of the brushless configuration relative to the commutator motor are increased complexity in the electronic controller and need for shaft position sensing.

Main advantages of the BLDC motor drives are high efficiency, low maintenance and long life, low noise, control simplicity, low

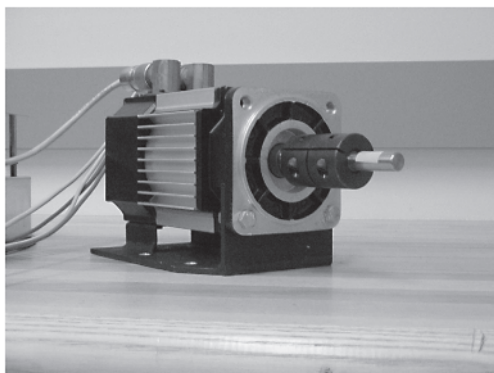


FIGURE 8.2 Typical BLDC motor, developed by Infranor Inc., Naugatuck, CT.

weight, and compact construction. On the other hand, the main disadvantages of the BLDC motor drives are high cost of the permanent magnet materials, the problem of demagnetization, and limited extended speed, constant power range (compared to a switched reluctance machine).

Brushless DC motors can be classified based on the shape of their back EMF: trapezoidal or sinusoidal. In a BLDC motor with trapezoidal back EMF, the permanent magnets produce an air gap flux density distribution that is of trapezoidal shape. These motors, compared to motors with sinusoidal shape back EMF, have higher torque and larger torque ripples. They are also cheaper and used for general applications. In a BLDC motor with sinusoidal back EMF, the permanent magnets produce an air gap flux density distribution that is sinusoidal. These motors, compared to motors with trapezoidal shape back EMF, have smaller torque ripples. They are also expensive and are used for servo applications.

8.1 BLDC MACHINE CONFIGURATIONS

Permanent magnet (PM) BLDC machines can be classified according to the type of the permanent magnet (ferrite, ceramic, alnico, or

rare earth), the shape of the back EMF waveform (trapezoidal or sinusoidal), the mounting of the permanent magnet (surface mounted or interior-mounted), the direction of the magnetic flux (radial or axial), the configuration of the windings (slot windings or slotless surface windings), or the power electronic drive (unipolar drive or bipolar drive).

Permanent magnet BLDC motors are classified as surface-mounted permanent magnet (SMPM) or interior-mounted permanent magnet (IPM) types. Figure 8.3 shows these two configurations. In the case of the surface-mounted permanent magnet machine, the magnets are mounted on the surface of the rotor, while for the interior-mounted permanent magnet machine, the magnets are inside the rotor. In the surface-mounted machine, the air gap might be nonuniform, while for the interior mounted machine, the air gap is uniform.

The stator shape of the PM BLDC motors can be configured with slots (slotted type) or without slots (slotless type); the slotless

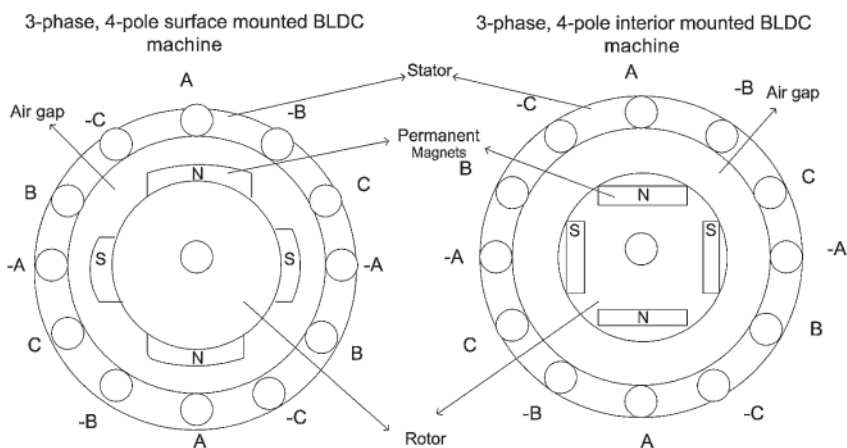


FIGURE 8.3 Surface-mounted and interior-mounted BLDC machines.

windings are also called surface winding or air gap winding. There is a special trend to use slotless BLDC motors especially in low-power and high-speed, high-performance applications. A method to eliminate the cogging torque in BLDC machines is to eliminate its source: the reluctance changes in the magnetic circuit during the rotation of the PM around the stator. In a traditional brushless motor, copper wires are wound through slots in a laminated steel core. As magnets pass by the lamination shoes, they have a greater attraction to the iron at the top of the laminations than to the air gap between shoes. This uneven magnetic pull causes cogging, which in turn increases motor vibrations and noise. Therefore, the key to smooth brushless performance centers on a slotless stator. Additionally, a slotless design significantly reduces damping losses.

Figure 8.4 shows the permanent magnet rotor of a three-phase, 1-hp BLDC motor; Fig. 8.5 shows the stator of a three-phase, 1-hp BLDC motor; and Fig. 8.6 shows the rotor and stator of a three-phase, 1-hp BLDC motor.

The BLDC motor consists of a stator, which contains the stator windings, and a rotor, on which permanent magnets are mounted. These magnets supply the field flux. The classic converter for the

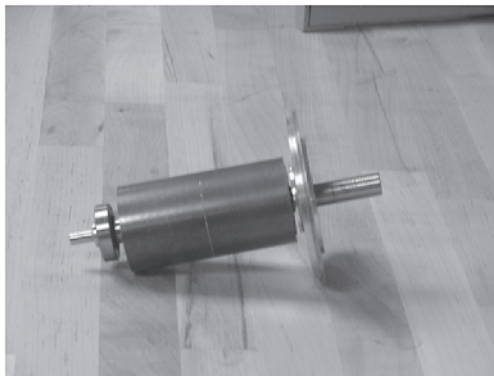


FIGURE 8.4 Permanent magnet rotor of a three-phase, 1-hp BLDC motor.



FIGURE 8.5 Stator of a three-phase, 1-hp BLDC motor.

BLDC motor is nothing but a DC/AC three-phase inverter, as shown in Fig. 8.7. The DC link voltage can be obtained from a pulse width modulation (PWM) rectifier from the AC supply, as shown in Fig. 8.8. A simple diode bridge can also be used.

To switch the coils in the correct sequence and at the correct time, the position of the rotor field magnets must be known. For

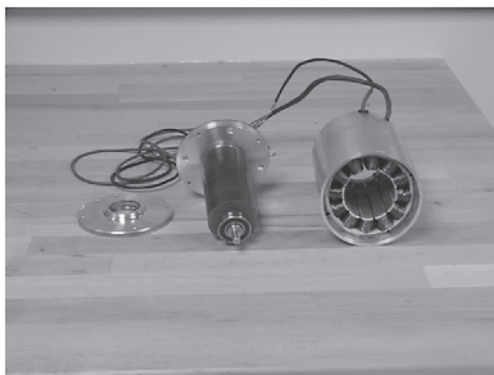


FIGURE 8.6 Rotor and stator of a three-phase, 1-hp BLDC motor.

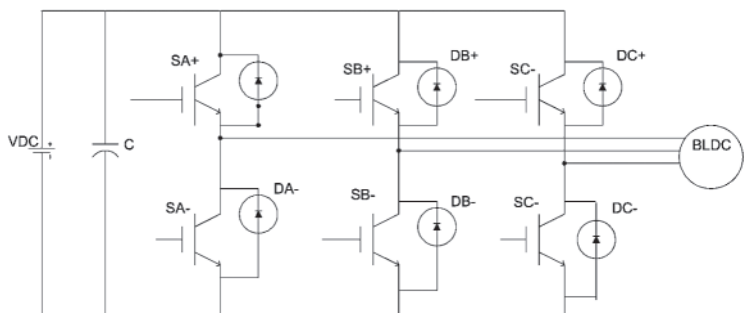


FIGURE 8.7 Classic BLDC power electronic driver.

locating the rotor field magnets, an absolute sensing system is required. An absolute sensing system may consist of Hall sensors or optical encoders.

The function of the controller is to switch the right currents in the right stator coils at the right time in the right sequence by taking the information supplied by the sensor and processing it with preprogrammed commands to make the motor perform as desired.

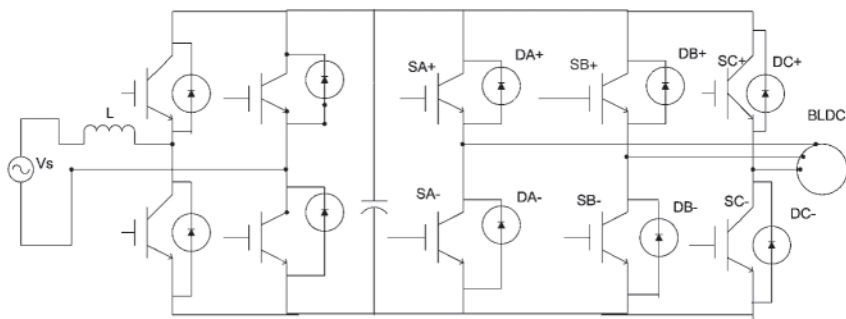


FIGURE 8.8 A typical BLDC driver with a PWM rectifier at its front end.

8.2 MODELING

A BLDC machine model is shown in Fig. 8.9. As shown in this figure, R is the phase resistance; L is the phase inductance; and E_A , E_B , and E_C are phase back EMF voltages. The waveforms are shown in Fig. 8.10.

Motor terminal voltage for a three-phase full bridge inverter with six switches and Y-connected motor can be expressed as follows:

$$V_{DC} = E_f + 2 R i_a + 2 L \frac{di_a}{dt}$$

Assuming switches are ideal and the EMF between conducting phases is constant (trapezoidal EMF), the instantaneous armature current can be written as follows:

$$i_a(t) = \frac{V_{DC} - E_F}{2 R} \left(1 - e^{\frac{R}{L}t} \right) + I_0 e^{\frac{R}{L}t}$$

We can express the EMF simply as a function of rotor speed:

$$E_f = k_e n$$

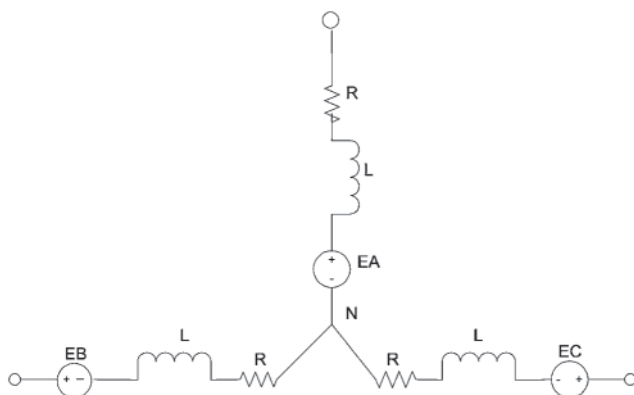


FIGURE 8.9 Equivalent circuit of a BLDC machine.

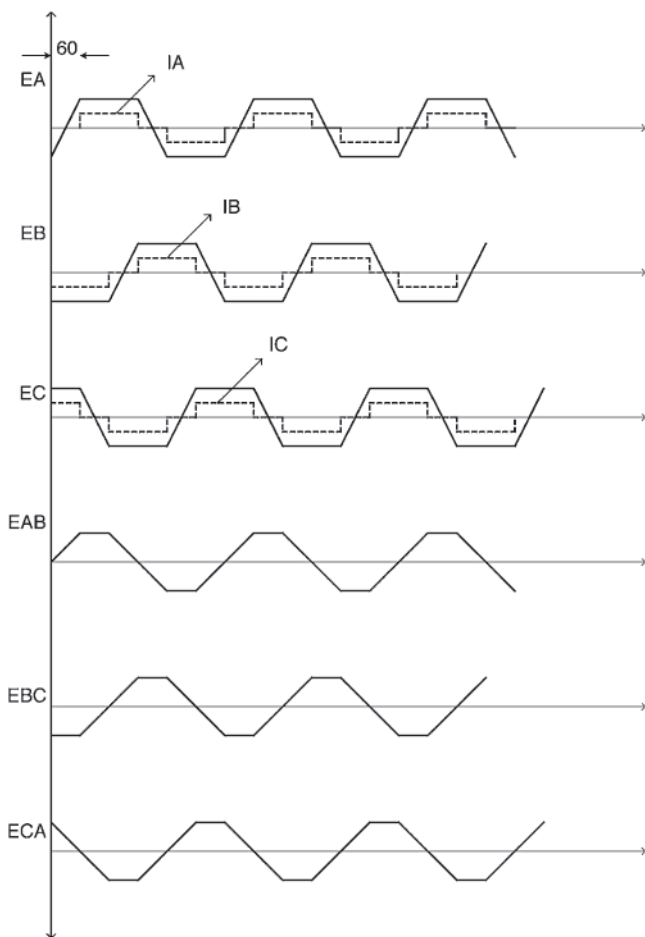


FIGURE 8.10 Voltage and current waveforms as a function of rotor position.

Torque equation is similar to a conventional DC commutator motor and can be written as follows:

$$T_d = k_t i_a$$

The average developed torque can be maximized and torque ripple can be minimized if the EMF voltage waveform has a trapezoidal shape. Trapezoidal waveform can be achieved by switching the MOSFETs or IGBTs in such a way that two-phase windings are always connected in series during the whole conduction period of 60 degrees. In addition, proper shaping and magnetizing of the permanent magnets and stator windings are important factors to obtain the trapezoidal waveform. Owing to manufacturing tolerances, armature reactions, and other parasitic effects, the EMF waveform is never ideally flat. However, a torque ripple below 5% can be achieved.

Power density and torque density are the measures to judge how the active materials of a BLDC motor are best utilized. NdFeB

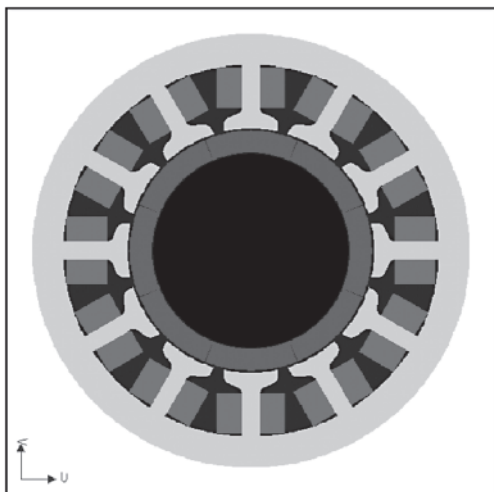


FIGURE 8.11 Geometry of a three-phase, 1-hp BLDC motor.

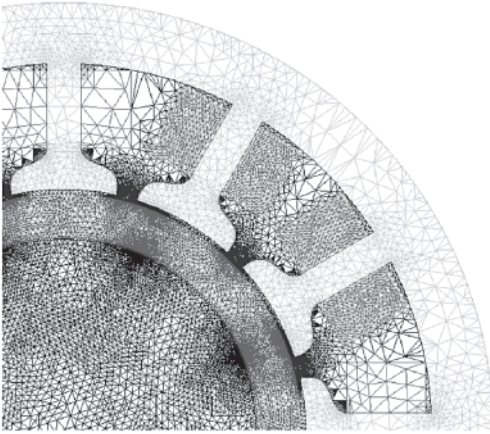


FIGURE 8.12 Enlarged view of the electromagnetic mesh of the three-phase, 1-hp BLDC motor.

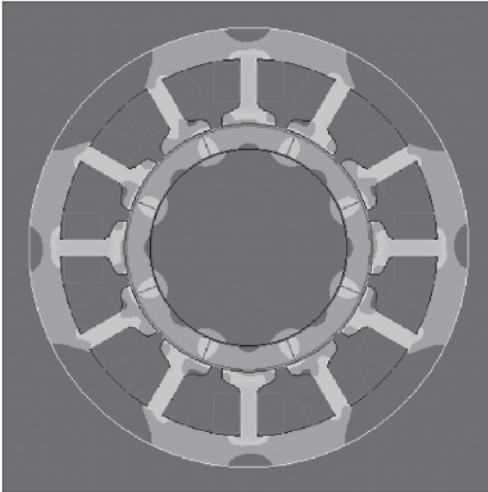


FIGURE 8.13 Magnetic flux density of the three-phase, 1-hp BLDC motor.

magnets offer the highest energy density at reasonable costs. Their major drawback, compared to SmCo, is temperature sensitivity. When using NdFeB magnets, the motor's temperature must be kept below 170–250°. Since the rotor losses are small, passive cooling is employed for the rotor. The main dimensions (inner stator diameter and effective length of core) for the BLDC are determined by rated power output, air gap magnetic flux density, and armature line current. Geometry of a three-phase, 1-hp BLDC motor is shown in Fig. 8.11.

Using a finite element (FE) software package such as Maxwell 2D (Ansoft Corp.) a BLDC machine can be analyzed and various solutions presented. The software generates an initial mesh and then refines the solution to achieve the required precision. An enlarged view of the final mesh is shown in Fig. 8.12. Magnetic flux density is shown in Fig. 8.13.

8.3 BLDC POWER ELECTRONIC DRIVERS

The permanent magnet BLDC motor shares the same torque-speed characteristics and the basic operating principles of the brushed DC

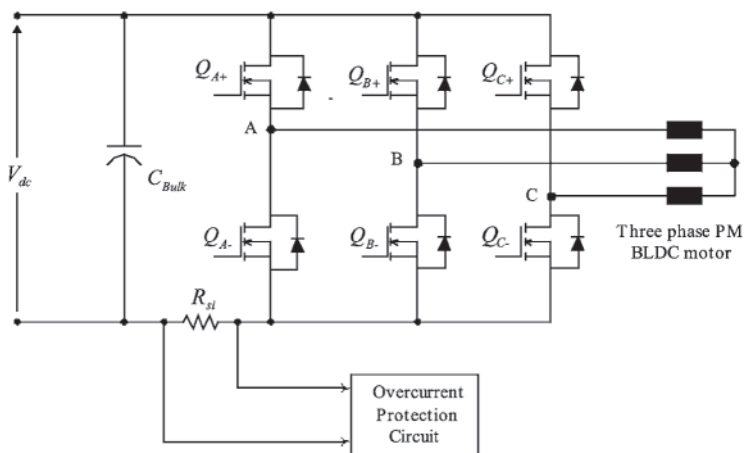


FIGURE 8.14 Three-phase MOSFET inverter.

motor. The main difference is that the field windings are replaced by permanent magnets and the commutation is done electronically. Using permanent magnets and eliminating the brushes offers many distinctive advantages, such as high performance torque control, low torque ripples, long life, high power-to-weight ratio, low noise and low electromagnetic interference, better heat dissipation, low maintenance, and very high speed of operation.

The power electronic driver for the BLDC motor can be an IGBT-based inverter, as shown in Figs. 8.7 and 8.8. It can also be a MOSFET-based inverter as shown in Fig. 8.14. An IGBT-based driver is usually used for high-power or high-voltage applications.

Figure 8.15 shows the three-phase voltage and current waveforms for a trapezoidal back EMF BLDC machine. In order to maintain the current as shown in Fig. 8.15, a hysteresis (bang-bang) control technique can be used. With the hysteresis control, the current is directly controlled; therefore, output torque of the

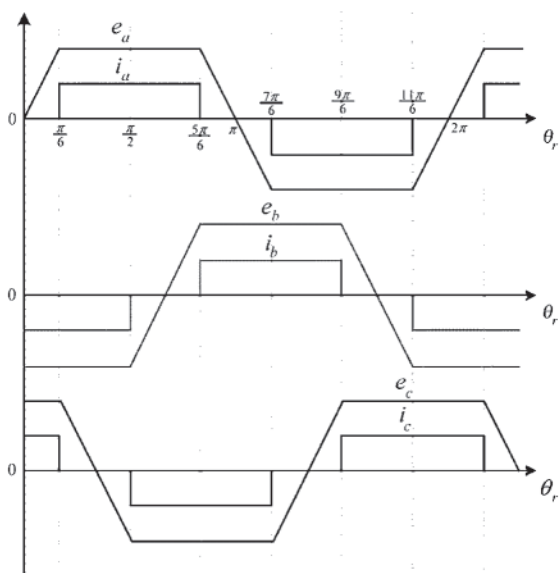


FIGURE 8.15 Ideal back EMF and phase current waveforms of the BLDC motor.

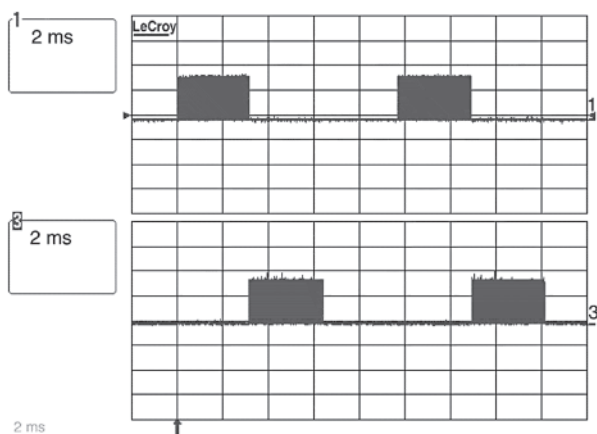


FIGURE 8.16 Driving pulses for Q_{A-} and Q_{B-} of inverter in Fig. 8.14, 10 V/div.

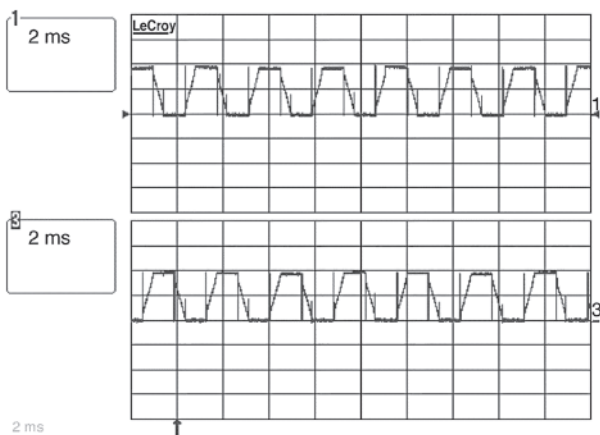


FIGURE 8.17 Voltages of phase A and phase B of the driver shown in Fig. 8.14.

motor is controlled. However, the switching frequency is variable. In order to have a constant switching frequency, a pulse width modulation technique can be used. There are many integrated circuits (ICs) available in the market that use PWM techniques. The advantage is that the average of the applied voltage to the motor terminals is directly controlled. Therefore, speed of the motor is directly controlled by changing the duty cycle of the PWM switching scheme. Simplicity is another advantage of the PWM methods.

In Fig. 8.14, for overcurrent protection, sense resistance R_{si} is used. The sense voltage over R_{si} , which is proportional to the load current, is fed into a comparator on the main control board. The overcurrent circuit limits the motor current. Driving pulses and phase voltages for the inverter in Fig. 8.14 are given in Figs. 8.16 and 8.17, respectively.

8.4 SENSORLESS TECHNIQUES FOR BLDC MOTOR DRIVES

Brushless DC motor drives require rotor position information for proper operation. Position sensors are usually used to provide the position information for the driver. However, in sensorless drives, position sensors are not used. Instead, position information is obtained indirectly. Advantages of sensorless drives include increased system reliability, reduced hardware cost, reduced feedback units, and decreased system size. In addition, they are free from mechanical and environmental constraints. However, sensorless techniques may affect system performance. Low-speed sensorless operation is also difficult.

Many model-based sensorless techniques have been proposed. In these methods, a model of the machine is used to obtain the position information from measured signals such as voltages and currents. Based on the model, usually a linear or nonlinear equation for position is solved. For example, in a d-q model-based sensorless technique, the actual d-q transformed currents and voltages, those on a hypothetical axis offset from the d-q axis by a small angle $\Delta\theta$, the output voltages of the model on the hypothetical axis, and those on

the actual d-q axis are compared. The difference between the calculated voltages of the hypothetical axis considering $\Delta\theta = 0$ and the actual d-q axis voltages on the hypothetical axis considering $\Delta\theta$ gives the actual change in rotor position from the previously known position.

Many sensorless techniques are based on the back EMF of the machine. Generally, these techniques are used for BLDC machines with trapezoidal back EMF. For example, the zero crossing point of the back EMF voltage can be detected. In this scheme, the three terminal voltages and neutral voltage of the motor with respect to the negative DC bus voltage are measured. The terminal voltage is equal to the neutral voltage at the instants of the zero crossing of the back EMF waveform. In order to use the zero crossing point to derive the switching sequence, this point has to be shifted by 30 degrees. Therefore, in this method, speed estimation is required.

In the third-harmonic back EMF sensing technique, the position of the rotor can be determined based on the stator third-harmonic voltage component. To detect the third-harmonic voltage, a three-phase set of resistors is connected across the motor windings (Fig. 8.18). The voltage across the points P and Q is denoted by E_3 , and it determines the third-harmonic voltage. This voltage is integrated for a zero crossing detector. The output of the zero crossing detector determines the switching sequence for turning on the switches. The resistances and inductances are shown in the circuit of Fig. 8.18. The important point is that the summed terminal voltages contains only the third and the multiples of the third harmonic due to the fact that only zero sequence current components can flow through the motor neutral. This voltage is dominated by the third harmonic.

By integrating the voltage E_3 , we get the third-harmonic flux linkage λ_3 . The third-harmonic flux linkage lags the third harmonic of the phase back EMF voltage by 30 degrees. The zero crossings of the third harmonic of the flux linkage correspond to the commutation instants of the BLDC driver, as shown in Fig. 8.19.

The back EMF integration method is another sensorless technique. In this method, by integrating the back EMF of the unexcited phase, position information is obtained. The integration of the back EMF starts when the back EMF of the open phase

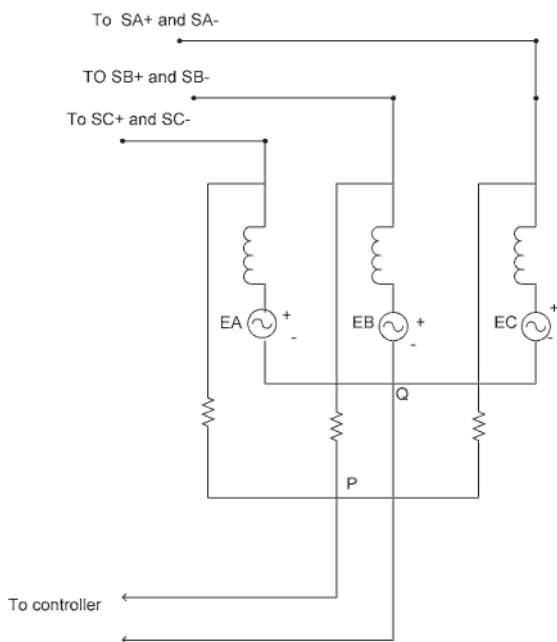


FIGURE 8.18 Resistors for the third harmonic back EMF sensing technique.

crosses zero. Here, speed estimation is not required. A threshold is set to stop the integration, which corresponds to a commutation point. Assuming trapezoidal back EMF, the threshold voltage is kept constant throughout the speed range. Integrating from the zero crossing point (ZCP) to the commutation point (CP) is constant (not a function of speed). Therefore, speed estimation is not required.

The freewheeling diode conduction-sensing technique uses indirect sensing of the phase back EMF to obtain the switching instants of the BLDC motor. Considering the 120-degree conducting wye-connected BLDC motor, one of the phases is always open. After opening the phase for a short interval of time, there remains a phase current flowing through a freewheeling diode. This open phase

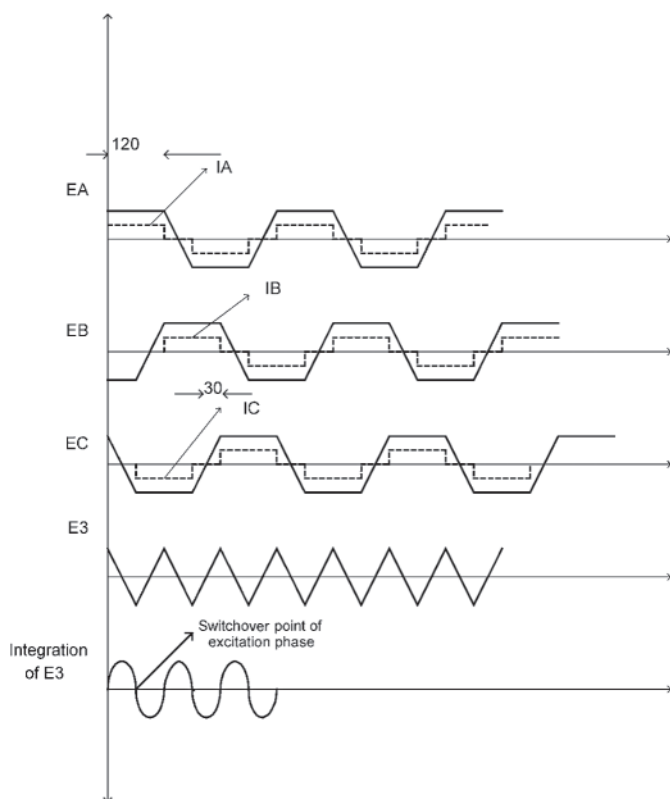


FIGURE 8.19 Phase currents and back EMF voltages, E_3 , and integration of E_3 versus rotor position.

current becomes zero in the middle of the commutation interval, which corresponds to the point where the back EMF of the open phase crosses zero.

Some sensorless techniques are also based on the magnetic flux. These methods are usually used for BLDC motors with sinusoidal back EMF. For example, in flux integration methods, instantaneous flux is obtained from the integration of the voltage

equation of the machine. By knowing the initial position, the relationship of the flux linkage to the rotor position, and machine parameters, the rotor position is estimated. The speed is determined by the rate of change of the flux linkage from the integration results.

Observer-based sensorless methods are generally used for BLDC motors with sinusoidal back EMF. In these techniques, a Kalman filter might be used. The Kalman filter provides an optimum observation from noisy sensed signals and processes that are disturbed by random noise. A mathematical model describing the motor dynamics is known. The rotor position can be determined based on the voltages and currents. The measured voltages and currents are transformed to stationary frame components. Using the state equations and a Kalman filter, the missing states (rotor position and velocity) are estimated. The estimated rotor position is used for commutation. The function of the filter is to correct the estimation process in a recursive manner. The filter constantly works on the output and corrects its quality based on the measured values. Based on the deviation from the estimated value, the filter provides an optimum output value at the next output instant.

In a state observer, the output is defined as a combination of the states. This output is compared with the equivalent measured output of the real motor. Any error between the two signals is used to correct the state trajectory of the observer. The accuracy of the position information depends on the stability of the observer. For the system to be stable, the gain of the system has to be optimized. Furthermore, initial information of the states is required for proper convergence of the observer.

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